Determining the Scattering Properties of Vertically-Structured Nepheloid Layers from the Fusion of Active and Passive Optical Sensors

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LONG-TERM GOALS

The optical impacts of a scattering benthic boundary layer are fairly obvious to in situ and remote sensing techniques that measure ocean color. These scattering layers cause an increase in light reflectance from positions above the benthos, a reduction in the penetrating photons to the bottom, and a decrease in photons scattered from the bottom back toward the surface. The net result is that these layers reduce the ability of active and passive optical instruments to retrieve estimates of bathymetry and bottom classification, as well as reduce the abilities of optical Mine Counter Measures (MCM) instrumentation to accurately image the bottom for mine-like objects. These scattering layers are not just optically active, they are in fact acoustically scattering as well. These scattering layers may introduce some real difficulties into both the optical and acoustical methods of detecting mine-like objects, reducing the viability of two major techniques in MCM. The project seeks to assess these the spatial extent of these nepheloid scattering layers with active and passive remote sensing techniques, and quantitatively resolve their vertical structure.

OBJECTIVES

1) To assemble simultaneously collected high resolution active (LIDAR) and passive (Spectral Imaging) optical remote sensing data in areas that are impacted by nepheloid scattering layers.

2) To develop the quantitative techniques to resolve the vertical structure of Inherent Optical Properties (IOPs) in the water column from optical remote sensing data.

3) To fuse the active and passive remote sensing data streams to produce digital information products of bathymetry, bottom type, and vertically-structured IOPs.

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14. ABSTRACT
The optical impacts of a scattering benthic boundary layer are fairly obvious to in situ and remote sensing techniques that measure ocean color. These scattering layers cause an increase in light reflectance from positions above the benthos, a reduction in the penetrating photons to the bottom, and a decrease in photons scattered from the bottom back toward the surface. The net result is that these layers reduce the ability of active and passive optical instruments to retrieve estimates of bathymetry and bottom classification, as well as reduce the abilities of optical Mine Counter Measures (MCM) instrumentation to accurately image the bottom for mine-like objects. These scattering layers are not just optically active, they are in fact acoustically scattering as well. These scattering layers may introduce some real difficulties into both the optical and acoustical methods of detecting mine-like objects, reducing the viability of two major techniques in MCM. The project seeks to assess these the spatial extent of these nepheloid scattering layers with active and passive remote sensing techniques, and quantitatively resolve their vertical structure.

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APPROACH

The use of spectral imagery for classification of benthic properties into information products such as bathymetry and bottom type has a long history in the open literature history (Ackleson, 1997; Dierssen et al., 2003; Lee et al., 1998; Lee et al., 1999; Lee and Carder, 2002; Louchard et al., 2003; Lyzenga, 1978; Maritorena et al., 1994; Mobley et al., 2004; O'Neill and Miller, 1989; Philpot et al., 2004; Philpot and Kohler, 1999; Philpot, 1989; Sandidge and Holyer, 1998; Stumpf et al., 2002). The desire to use spectral imagery instead of more traditional means of estimating this type of information via the use of in-water systems, e.g. bathymetric sounders, multi-beam sonar, and side-scan sonar, stem from the differences in deployment characteristics of the remote sensing and in-water platforms. These differences may be seen in Figure 1, where it is evident that the swath width of the in-water systems decreases substantially as the height of the sensor above the bottom decreases. This means that the effective data or information acquisition rate decreases significantly. In shallow waters less then 5 - 10 m, these systems may be costly, as the drafts of the survey ships are too deep to operate safely requiring the use and coordination of a fleet of small craft. This may just be too cost prohibitive to collect the data, as the time on station may exceed budgetary constraint. In addition to budgetary constraints, the U.S. Navy has operational requirements that may not allow for surface vessels to be exposed in the near shore environment. These “access denied” areas require a mechanism to remotely assess the bathymetry and bottom type, with the benefit of the in water systems.

These budgetary and access constraints have focused a tremendous amount of interest on the capabilities of retrieving marine environmental information from passive spectral remote sensing. Early efforts focused on single or multi-wavelength approaches (Ackleson, 1997; Lyzenga, 1978; Maritorena et al., 1994; Philpot, 1989) that use a form of the two-flow equation (Mobley, 1994) to estimate the bathymetry based upon assumptions about the water clarity and bottom reflectance characteristics. The regression analysis of the predicted bathymetry versus true bathymetry of these early efforts demonstrated admirable results. Yet, frequently there were off-sets in the estimates that were ascribed to environmental errors, including errors in the estimation of water clarity or bottom types. This problem was (is) more specifically related to the need to know the Inherent Optical Properties (IOPs) of the water column, which includes the bottom reflectance, before one could use the two-flow equation in remote areas with little field data or validation.

The shallow water inversion problem in its most general form is the radiative transfer equation. The radiative transfer equation describes the gain and loss of photons along a given path through the interaction equations that govern absorbance, scatterance, and transmittance (Mobley, 1994). The application of the radiative transfer equation to the shallow water inversion problem requires one to simultaneously solve for bathymetry, bottom reflectance, and vertically-structured IOPs when attempting to retrieve an optical reflectance signal (Figure 2). This, of course, was known by earlier investigators, but the number of degrees of freedom (i.e. the number of spectral bands) in the reflectance data was limited in these previous studies, and advancement required working with the available data.

HyperSpectral Imaging (HSI) offers the potential to increase the number of degrees of freedom by which to invert the radiative transfer equation in shallow waters (Lee et al., 1998; Lee et al., 1999; Lee and Carder, 2002; Louchard et al., 2003; Mobley et al., 2004; Mobley et al., 2002; Sandidge and Holyer, 1998). This allows for multiple approaches to resolving the simultaneous variations in bathymetry, bottom reflectance, and vertically-structured IOP. Two of the more common approaches discussed include lookup table approaches that match presolved solutions to the radiative transfer

equation to the HSI and neural network approaches that let the scene or some limited number of presolved solutions train the retrieval algorithm (Philpot et al., 2004). Both of these approaches use computationally intensive processing, which employ the greater degrees of freedom offered by the HSI data, to retrieve a more robust estimate of bathymetry.

There are other optical remote sensing means to accomplish bathymetric soundings. Specifically active airborne remote sensing in the form of LIght Detection And Ranging (LIDAR) has some of the same advantages as the passive HSI (Guenther, 2001; Guenther et al., 2000; Irish et al.), e.g. constant swath over changing bathymetry, as well as some others, such as 24/7 operations and International Hydrographic Office (IHO) Level 1 qualification for bathymetry sounding. The LIDAR bathymetry soundings are less sensitive to IOP variations, and the quality of the data (as recognized by the USACE and IHO) provides bathymetry estimates sufficient for nautical charting. And after nearly 10 years of development, the Naval Oceanographic Office (NAVO) took delivery of the Compact Hydrographic Airborne Rapid Total Survey (CHARTS), which included the latest version of the Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS). This system provides operational optical sounding from an airborne remote sensing vehicle.

The availability of two optical techniques to retrieve a similar environmental attribute offers the potential for data fusion applications that, at a minimum, can identify geographic areas of high error potential. The comparison of the two sounding estimates may also offer system performance evaluations that help define and refine total data quality. Lastly, the true fusion of the active and passive data stream may yield higher quality estimates of the vertically-structured IOPs, as well as bottom type retrievals. This would provide validation and calibration resources to both data streams, which in turn would provide the highest quality environmental digital mapping products to civilian and military users.

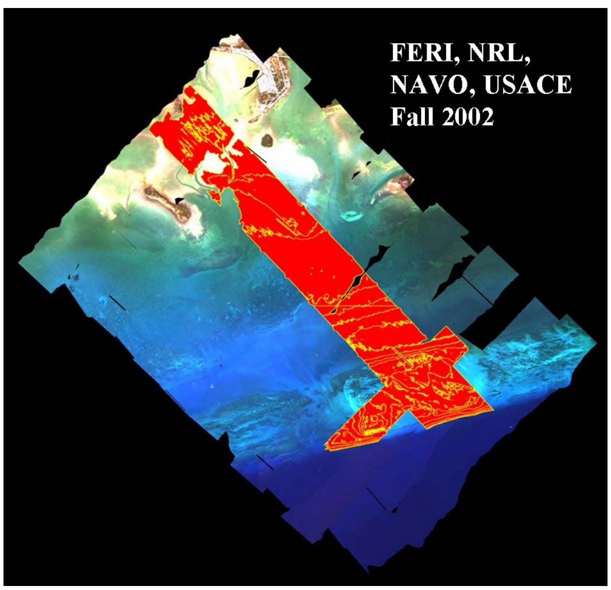

Figure 1. FERI/NRL/NAVO/USACE Joint Hyperspectral/LIDAR Experiment October, 2002. RGB image of the HSI data with SHOALS coverage colored in red. This red area represents comparisons of > 1.9 x 10^6 co-located sounding with the hyperspectral estimated bathymetry.

WORK COMPLETED

In October of 2002, a joint FERI/NRL/NAVO/USACE HSI/LIDAR experiment was conducted off of Looe Key, FL (Figure 1). This experiment yielded high quality HSI data at a 2 m resolution and bathymetric LIDAR data at a 4 m resolution. The joint data set allowed for the advancement and validation of a previously generated Look-Up-Table (LUT) approach to the simultaneous retrieval of bathymetry, IOPs, and bottom type (see Mobley, N0001400D01610001, and Bissett, N000140110201). In 2004, FERI collected hyperspectral imagery Humboldt Bay, CA, which is a significantly more turbid than the Florida Keys (Figure 2). During July of 2004, active acoustic bathymetry from multibeam and single beam sonar was collected over the Bay, which will be used for active/passive fusion studies in FY 2006 (Figure 3).

Figure 2. FERI HSI of Humboldt Bay, CA collected October 27, 2004. Multibeam and singlebeam sonar were collected within the entire bay during July 2005.

Results from related projects (Bissett, N000140110201, Mobley, N0001404C0218 and N0001404M0108) suggested that prior expectations of increasing the size of our LUT database (from 12,000 separate spectral Rrs entries to 235,625 entries) would reduce the bathymetric errors. However, contrary to expectation, the bathymetric errors increased with the increase in the number of database entries. This was driven mainly by sensor and environmental noise in the imagery data, as well as database entries that were not representative of the bottom type and water quality of the image location. These results forced us to revisit the spectrum matching selection criteria, with emphasis on using thesholding and other spectral weighting techniques to reduce the bathymetric error rate in the Looe Key imagery.

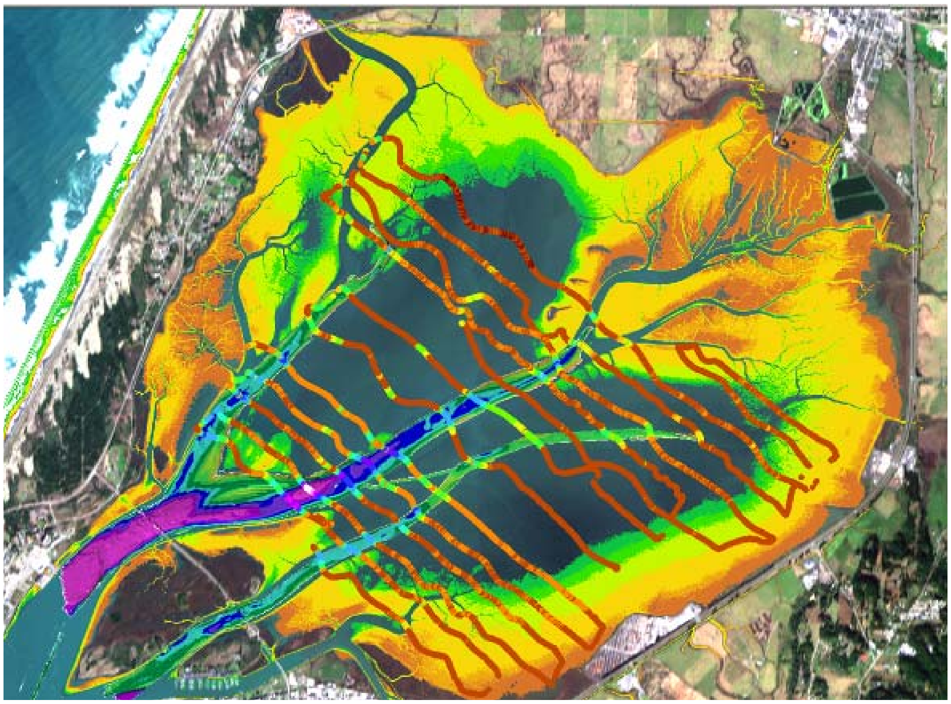

Figure 3. Combined HSI RGB with 2002 topographic LIDAR bathymetry, and 2005 multibeam bathymetry and single beam bathymetry for northern Humboldt Bay.

RESULTS

In the current LUT spectral matching, each wavelength is assigned equal importance. RMS error is calculated between the image spectrum and LUT spectrums, and the spectrum with the least RMS difference is chosen as the best match. An inherent problem with this approach is that in hyperspectral remote sensing of costal environment, the wavelengths that has the most information changes drastically depending on the environmental factors like bathymetry and bottom type. When comparing spectrums for very shallow waters, the wavelengths that contain the most differentiable information are very different from when comparing deep water spectrums. For example, the IR wavelengths generally have no information in waters deeper than one meter, while for shallow regions with green bottom, it has the most information. Thus, most of the signal recorded in the IR region for deeper waters is sensor noise and giving equal importance to IR wavelengths in matching can result in high susceptibility to noise. On the other hand excluding the IR wavelengths in matching can result in lower classification accuracy in shallower depths. A mechanism needs to be developed in consideration of the above observations, which can help determine the usefulness of a particular wavelength in spectrum matching.

The approach taken was to try simplistic algorithms first and keep mutating it into more complex ones according to the observations and results. The first method tried was static thresholding. The wavelengths to be used in the matching were predetermined and it remained same for all the image spectrums. The spectrums were matched only on the wavelengths selected and the rest of the spectrum was ignored. Initially all the wavelengths available were used in LUT matching. The base-level LUT has wavelength range of 400nm-760 nm, and was taken as the initial threshold. Figure 4 shows the absolute depth difference between the depth derived from PHILLS image using the LUT technique and

SHOALS image. As seen from the image, the classification error at some places was more than 8 meters. This was considerably worse compared to the classification obtained using the 12K LUT.

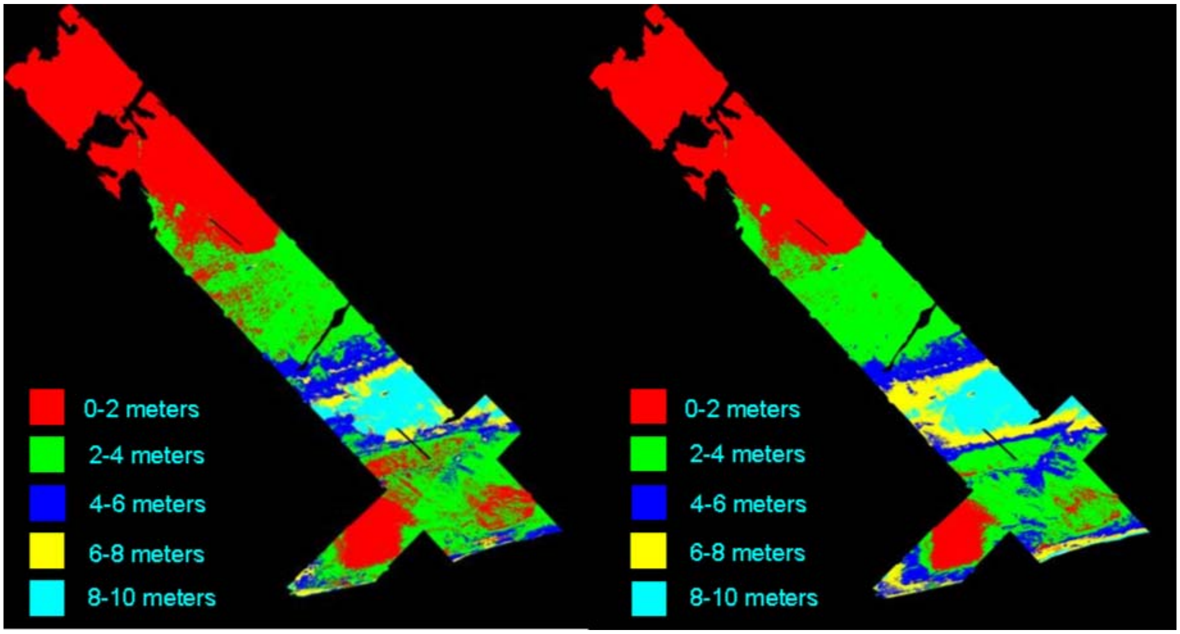

Figure 4. Absolute difference in depths between 200K LUT using static thresholding. (LEFT) Bathymetric errors between LIDAR and HSI LUT estimates using full HSI spectrum to 760 nm. (RIGHT) Absolute difference in depths using static thresholding at 660 nm; note the decrease in errors in the deeper regions of Hawk Channel with the reduce spectral resolution.

As any wavelength beyond 660 would not have any signal, except for very shallow depths, 660 nm was selected as the second threshold. Thus the spectrum was matched only between 400-660 nm wavelengths and rest of the spectrum was discarded. The right Figure 1 shows the classification accuracy by this method. As there was a slight improvement in the classification accuracy by selecting a narrower threshold of 660 nm, the threshold was made narrower until the accuracy started to reduce again. It was noted that when thresholding was done at 575 nm, the classification accuracy was the best on average as shown in Figure 5.

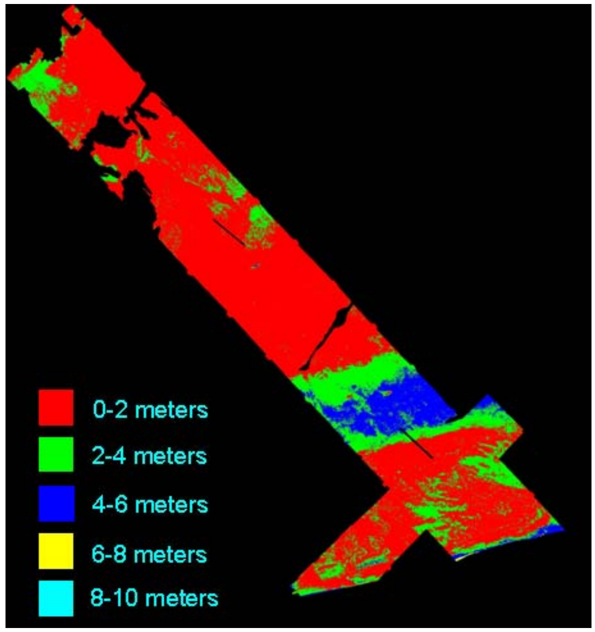

Figure 5. Absolute difference in depths using static thresholding at 575. This wavelength threshold provided the best overall bathymetry match between the LIDAR and HSI LUT.

As seen in the 5, thresholding at 575 nm gives good classification accuracy in deeper depths but is significantly worse in shallower depths. This is because shallower depths have a lot of information in the 575-700 nm wavelength range that is ignored in the thresholding. Figure 6 is a plot of few spectrums from the upper left corner of the image where classification accuracy for the image using 575 thresholding was worse then the 660 thresholding image. The figure clearly explains why the 575 thresholding performs poorly at shallow depths. Shallow water spectrums have information between 575 and 660 nm which is completely excluded by thresholding, and thus it retrieves substantially deeper depths. On the other hand, even the 14.25 m deep image spectrum has response in IR wavelengths. This is a result of the sensor and environmental noise. Due to this noise, artificial dark bottoms were retrieved, which forces the underestimation of the depths in classification. Figure 6 shows the bottom selected by both methods. The results confirm the hypothesis that the usefulness of any wavelength in matching two spectrums is a function of the features of those spectrums.

It may be impossible to find a wavelength that can be used to match all the spectrums. However, it may be possible to use the fusion of active data to more clearly select the appropriate wavelength range for retrieval of bathymetry, bottom type, and water column IOPs. This will allow us to increase the accuracy of our retrievals, while reducing the impact of sensor and environmental noise on the HSI LUT techniques. This will be the focus of our FY 2006 work, with both the Looe Key and Humboldt Bay data.

IMPACTS/APPLICATIONS

The ability to use active and passive optical data from aircraft and satellite data streams will provide the mechanism to deliver 24/7 performance prediction characteristics for the deployment of organic optical and acoustic MCM systems. In addition, remotely sensed high resolution bathymetry is critical for the prediction of local currents in access denied areas, providing important BSE mission planning to SPECWARCOM.

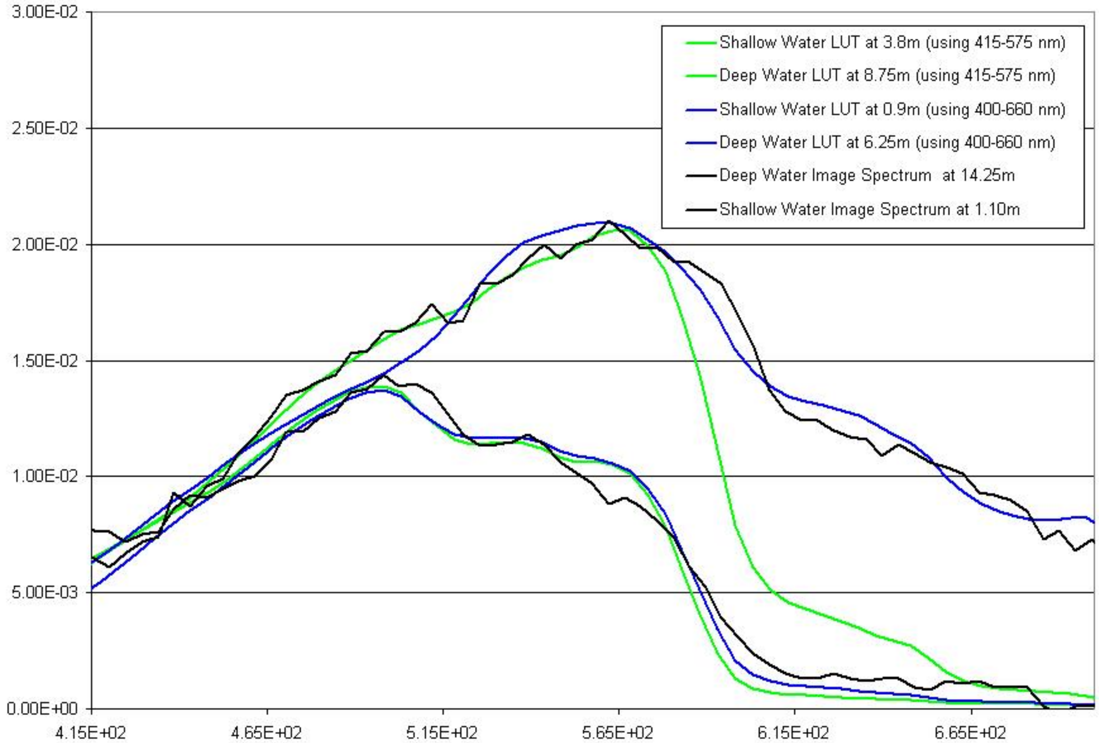

Figure 6. Spectrums plots for regions where static thresholding had considerably low and high classification accuracy. The shallow water (brighter grouping) had better matches using larger thresholds because of the real NIR information in the image spectrum. However, the NIR information was of lower quality in the deeper water, causing significant errors in the larger threshold retrievals.

RELATED PROJECTS

The work is part of a larger including C. Mobley of Sequoia Scientific, Inc. (N0001404M0108), and it closely interacts with the project led by C. Mobley (N0001404C0218) and PI Bissett (N000140110201).

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HONORS/AWARDS/PRIZES

2004 Small Business of the Year, Finalist, Florida Environmental Research Institute, W. Paul Bissett, Ph.D., Executive Director, Greater Tampa Chamber of Commerce.